Connected and Learning Based Optimal Freight Management for Efficiency

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Cummins Inc.

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2022 DOE Vehicle Technologies Office Annual Merit Review (AMR)

Overview

Timeline

- Project Start Date: 10/01/2020
- Project End Date: 12/31/2023
- Percent Complete: 30%

Budget

- Total Project Budget: $3,177,151
  - Total recipient share: $1,177,151
  - Total federal share: $2,000,000
  - Federal share of expenditures*: $728,910
  - Recipient share of expenditures*: $448,549

* As of 03/31/2021 (does not include federal lab spending)

Barriers

- Efficient operation of future trucking freight transportation with emerging electrification, connectivity and automation is a complex decision-making problem for fleet owners to manage:
  - Different efficiencies and energy consumption depending on the type of powertrain and shipment decisions
  - Limited charging infrastructure to consider in routing and truck dispatching decisions
  - Complicated cost models and scenarios to plan for investment
  - Limited data to derive insight of technology impacts on system

Partners

- Cummins (lead)
- Venture Transport
- Argonne National Laboratory
- University of California, Berkeley
- Michelin North America

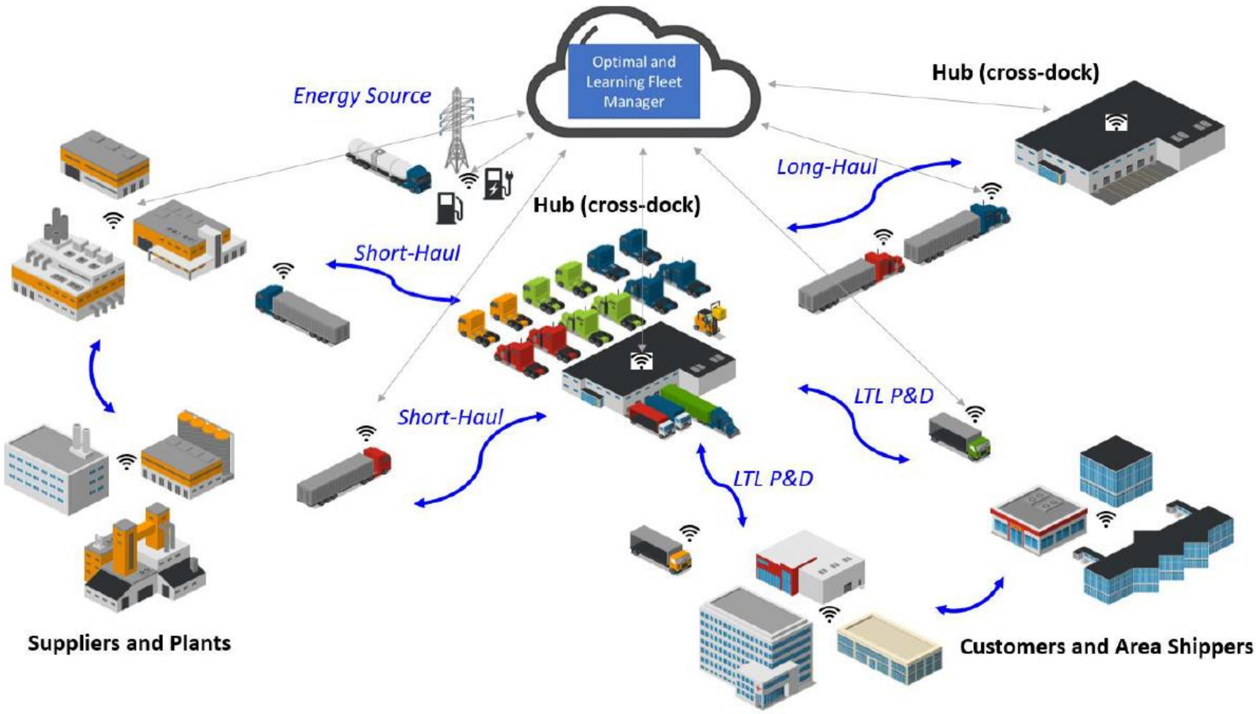
Relevance

Demonstrate ≥ ***20% fleet level WTW CO_2 (kg/ton-mile) reduction*** over a baseline fleet by

1) optimal adoption of emerging technologies
    - Advanced powertrain: Hybrid, FC, BEV
    - Connectivity and Automation: L3+, CACC, Tire
2) optimal operation using learning fleet optimizer
    - Truck Dispatching, Routing and Scheduling
    - Type (class 6 versus 8) and # of vehicles
    - Charge management
3) Minimizing cost/TCO

This will result in

- Paths to ≥ 20% fleet level WTW CO_2 reduction with minimum cost w.r.t. the baseline
- Assess different electrification & CAV scenarios on the path to target
- Learning fleet optimizer software for optimal and resilient fleet operation with emerging MDHD technologies in electrification and CAV



Trucking freight transportation

- is dominant mode of freight shipping in U.S.
- accounts for >20% of transportation energy consumption & GHG emissions.
- projected to grow and adopt electrification, connectivity and automation technologies.

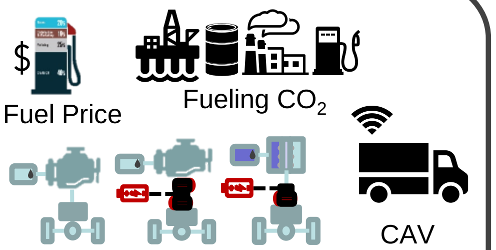
Key Milestones*

Budget Period	Start/End Date	Milestone	Type	Description
Complete 1	10/01/2020 – 12/31/2021	Complete Baseline Freight System Simulation Model Development and Validation with the Fleet Operation Data	Go/No Go	The baseline freight operation has been successfully evaluated in the freight system simulation model.
Ongoing 2	1/01/2022 – 12/31/2022	Demonstrate ≥20% Freight Operation Efficiency in Simulation	Go/No Go	The ≥20% improvement in freight efficiency has been demonstrated and the conditions under which the improvement is feasible are documented. This includes quantifications of the required targets for penetration of alternative powertrains, powertrain to route matching, and automation/connectivity technologies.
3	1/01/2023– 12/31/2023	Demonstrate ≥20% Efficiency Improvement on the Fleet with a Mix of Micro Simulation and Actual Fleet Operation	Technical	A ≥20% improvement in freight efficiency is demonstrated under real-world fleet conditions by the aggregate of all the technologies embodied in the project.

**Interim Milestones and Tasks are defined in the SOPO and PMP*

Approach

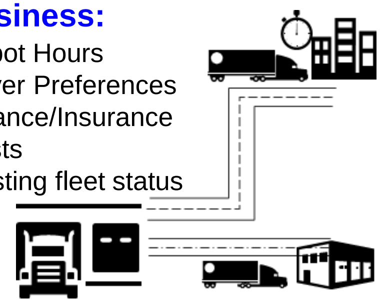
1. **Technology:**



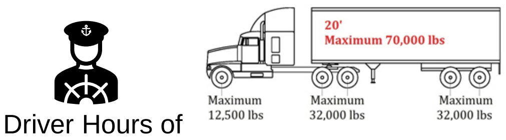
2. **Infrastructure**:

3. **Business:**

Depot Hours
Driver Preferences
Finance/Insurance
Costs
Existing fleet status



4. **Regulatory**:



5. **Customer:**

Fleet Optimizer

Per Year

Planning Optimizer with Learning

Per Day

Daily Optimizer with Learning

Decision Variables

1. New vehicle type and class (ICE, BEV, FC, etc.)
2. Charging decision (location, type, number)
3. Connectivity and automation features
4. Tires (standard / low RR)

5. Routing/P&D sequence
6. Vehicle dispatching
7. Load scheduling
8. Charging & fueling schedule
9. Trip Time vs fuel economy tradeoff with CAV

Fleet

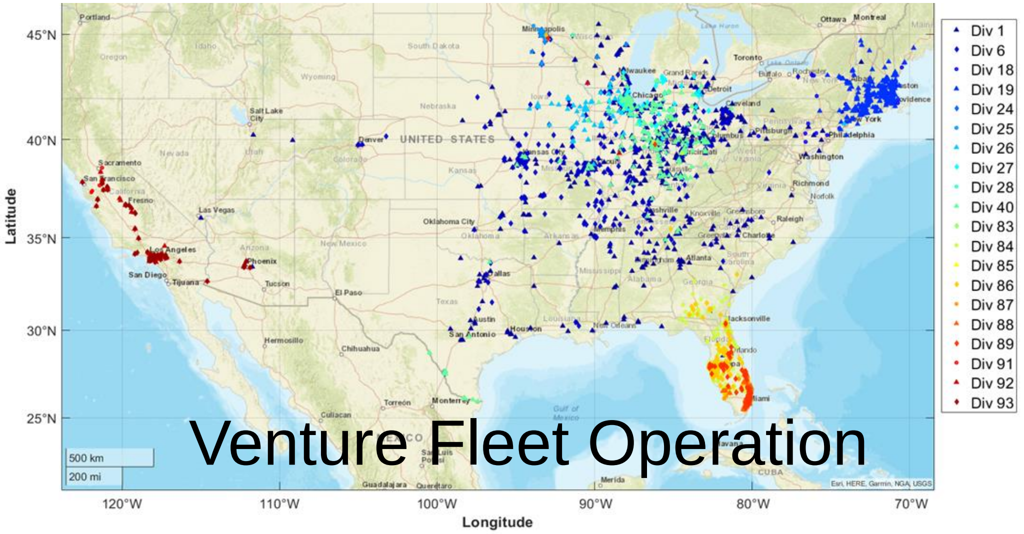
POLARIS Baseline Fleet Model/Real Fleet

- WTW CO_2 / ton-mile
- Successful / Failed trip
- Others e.g.
  - ➢ Energy/ Fuel consumption
  - ➢ Cost (post-calculated)

Data for Learning Algorithms

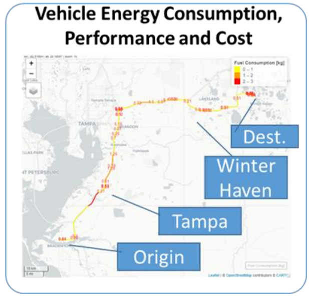
Technical Achievements: Fleet Baseline Model

- **Goal: simulate all of Venture fleet operations**
  - Baseline simulation: today's operations (routes, ..) and energy consumption
  - Simulate future fleet operation scenarios (Y2-Y3)
    - Predict routing and energy consumption with new technologies
    - Scale up impacts of optimization & learning models (by Cummins and UCB) to model impacts for the entire fleet
- **Innovations**
  - Data-driven energy analysis of Class 7/8 fleets
    - Large-scale data on payload and routes being used in the simulation
    - Real-world fleet operations are modeled, including payload
    - National, long-haul & regional fleets
  - Enhanced estimation of energy consumption in Autonomie
    - Ability to include grade profiles
    - Can now include payload
    - Modified key parameters including drag and rolling resistance
    - Reconfigured code to account for considerations including state-of-charge at beginning/end of trip



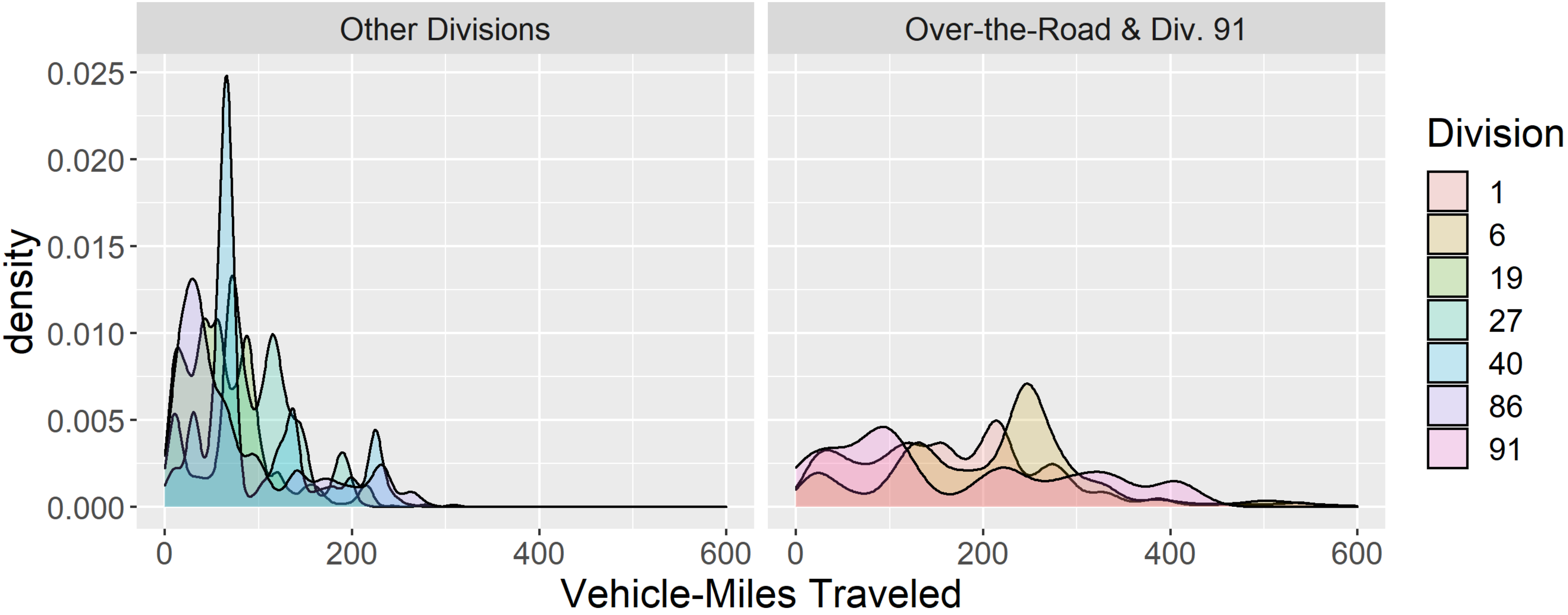
Metric	All Divisions	Selected Divisions
Number of Divisions	20	7
Number of Trucks	625	487
Sleeper/Day Cab (%)	46 / 54	56 / 47
Number of Routes	48,599	33,488
Number of Edges	98,357	65,411
VMT (mi)	10.0 Million	7.7 Million
Total Cargo (US ton)	826 Thousand	541 Thousand
Freight ton-miles (US ton-mile)	178 Billion	135 Billion

Over 3 months



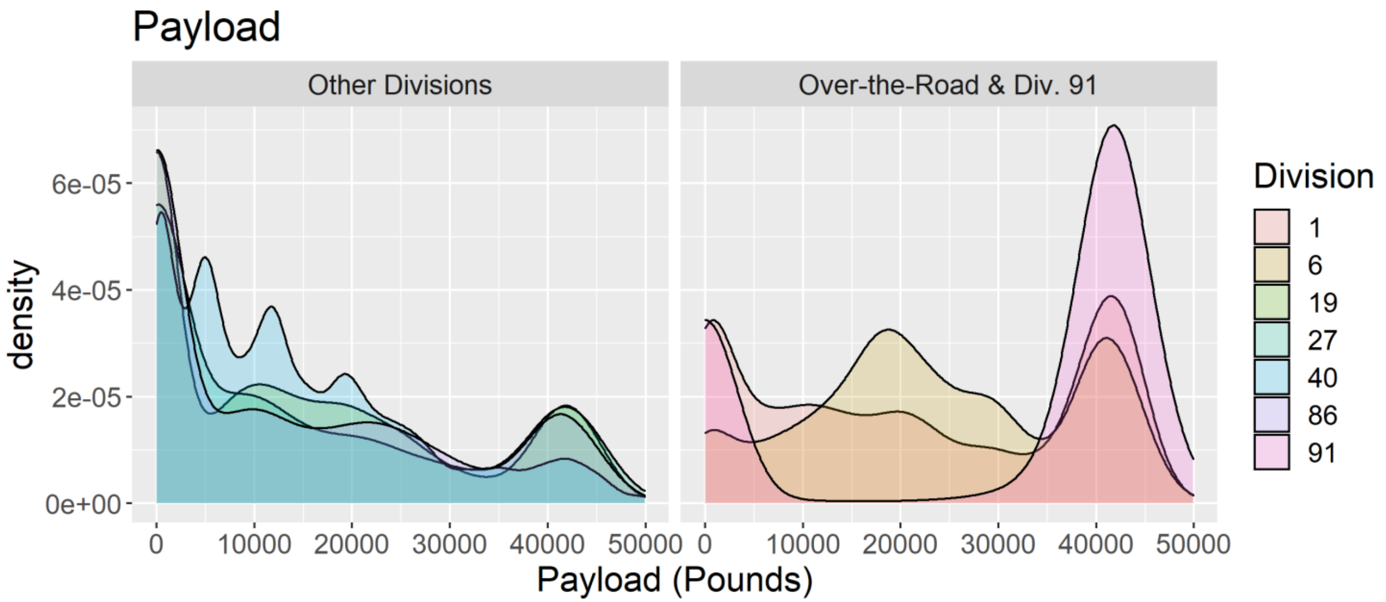
Technical Achievements: Fleet Baseline Model

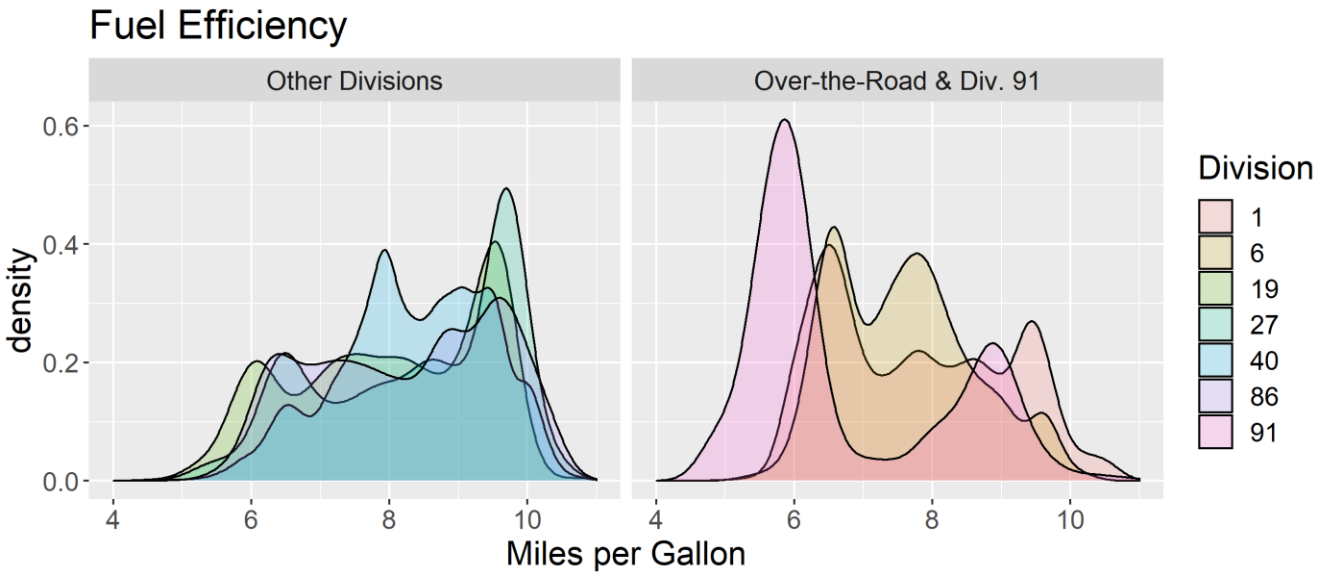
65,371 Trips by 487 Trucks Nationwide for 3-Month Period Are Simulated in POLARIS



Technical Achievements: Fleet Baseline Model

Operational Data Shows Lower Payloads for Regional Trips, Leading to Higher Simulated Fuel Efficiency

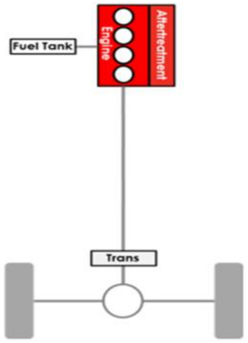


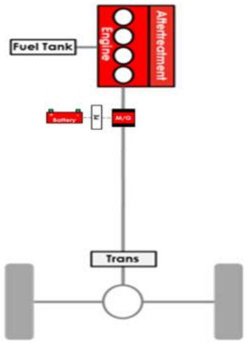


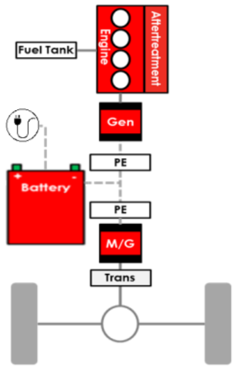
Technical Accomplishments:

Vehicle and Powertrain Models Development in Autonomie

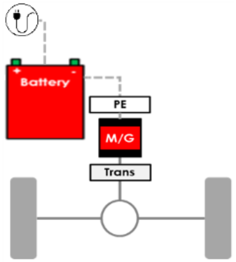
Conventional	Mild Hybrid	EREV Series
Diesel	Diesel	Diesel

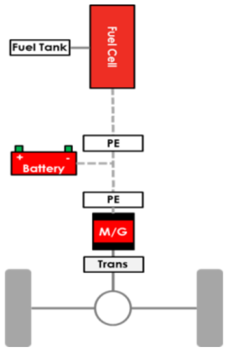


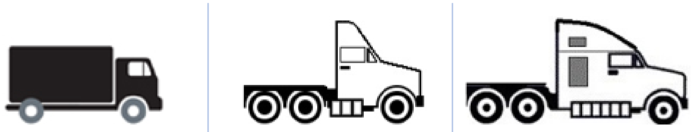




BEV	Fuel Cell
Electric	Hydrogen







Vehicle Class		Class 6 P&D	Class 8	
GVWR		19,501-26,000 lb	33,001-80,000 lb	
Application		P&D	Regional Haull / Day Cab	Linehaul / Sleeper
Conventional	Diesel	✓	✓	✓
Mild Hybrid	Diesel	N/A	✓	✓
EREV Series	Electricity/Diesel	✓	✓	✓
BEV	Electricity	✓	✓	✓
FC	H_2	N/A	✓	✓
Driving Range		150 mi/day	400 mi/day	500 + mi/day

*13 Truck models with different powertrain technologies developed.

'Autonomie Express' workflow

AUTONOMIE EXPRESS

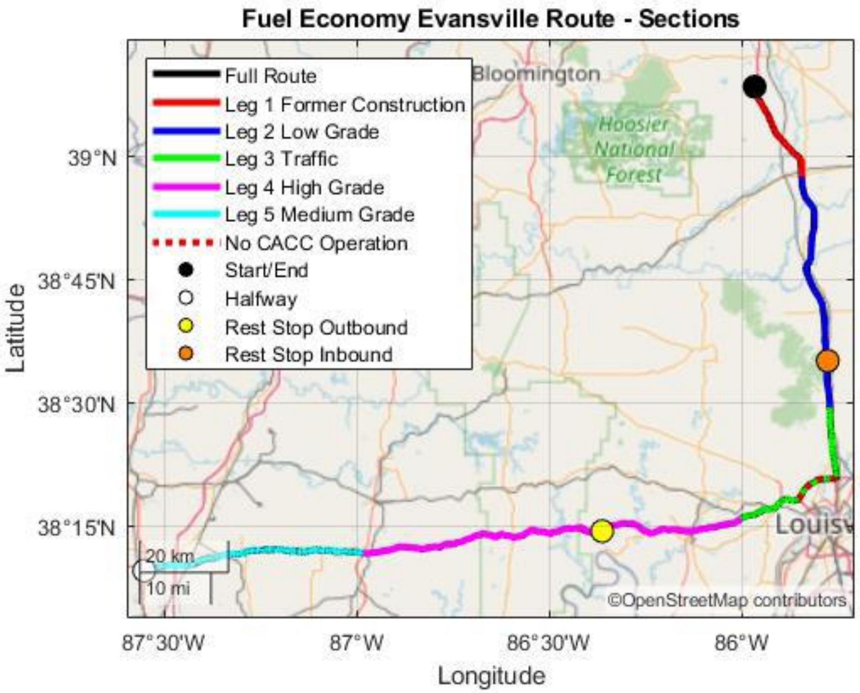
Compile vehicle models → Evaluate thousands of cycles with HPC → Post process results

Vehicles and processes developed in VAN023 & EEMS013 supported this work.

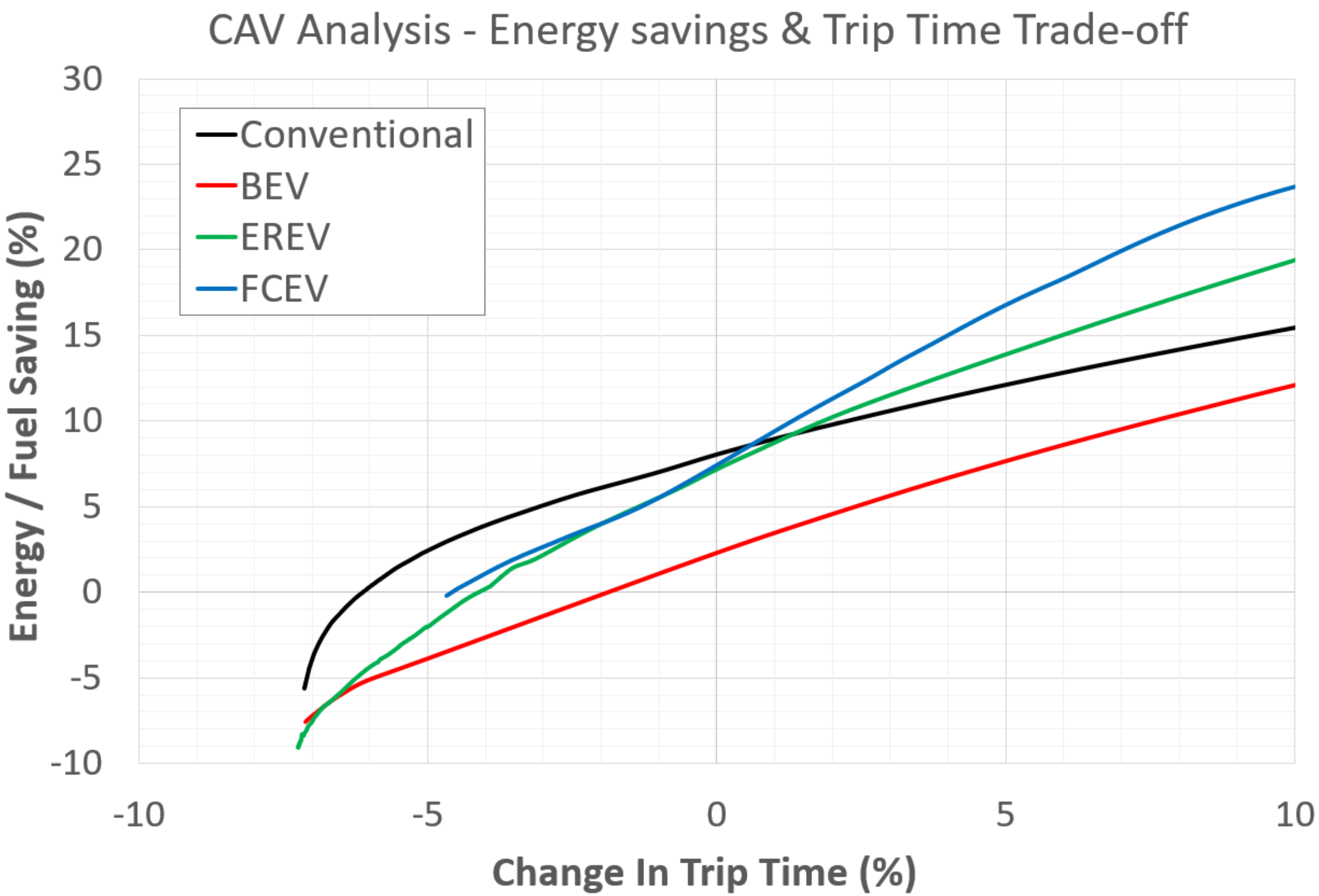
EREV: Extended Range Electric Vehicle
BEV: Battery Electric Vehicle

Technical Accomplishments:

Connectivity and Automation (CAV) Characterization



Representative Route
(DE-EE0008469 project)



- Trip time can be further optimized on fleet management level to reduce energy consumption with speed tradeoff.
- Energy saving of Eco-Autonomous Driving depends on powertrain. Other benefits exist e.g. regen braking reduction.
- Platooning: additional ~6% improvement with regenerative braking capability & ~2.5 for conventional.

Tire Characterization and Connectivity

Objective

Quantify the improvements in energy savings when accounting for information in real time about **resistance to motion forces** and **the tire locomotion capabilities** as a function of the vehicle operating conditions.

Progress on Measurement of Resistance to Motion Forces

- Test plan defined for measuring tire rolling resistance as a function of load, inflation pressure, speed, ambient temperature and road conditions (roughness and unevenness) established for several tires.
- Measurements completed for the tire rolling resistance as a function of load, inflation pressure, speed and ambient temperature completed for steer, drive and trailer tires characteristic to regional haul.

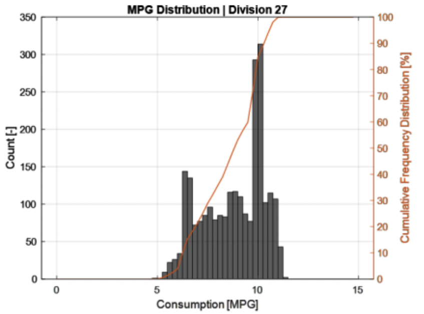
Progress on Measurement of Tire Locomotion Capabilities

- Test plan defined for measuring tire friction capabilities under acceleration for different loads and ambient temperatures established for different drive tire designs.

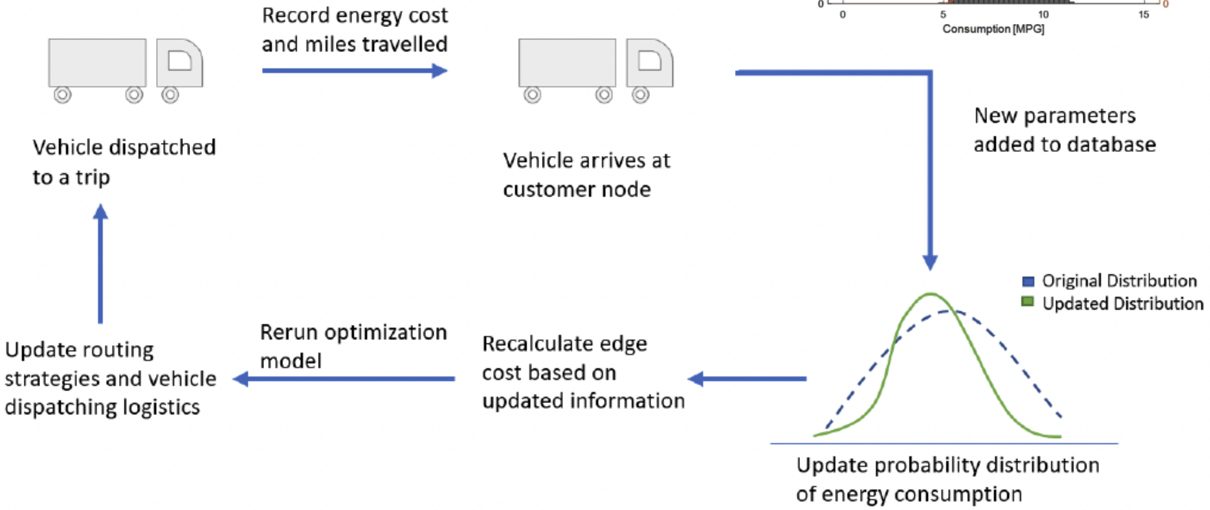
Next Steps

- Measurements of the tire rolling resistance as a function of road conditions for steer, drive and trailer tires.
- Measurement of tire friction capabilities under acceleration for different drive tire designs.
- Development of tire rolling resistance and locomotion models that can communicate in real time these tire performances to the vehicle through tire connectivity.

Learning Fleet Optimizer



- **Challenge:** Energy consumption is <u>uncertain</u> due to traffic, weather, payload, road conditions, etc.
- **State-of-Art:** Deterministic optimization will occasionally strand BEV trucks in real-world or yield overly-conservative solutions.
- **Approach:** Learning-based optimization uses data measured from daily operation to solve distributionally robust optimization.



Objective

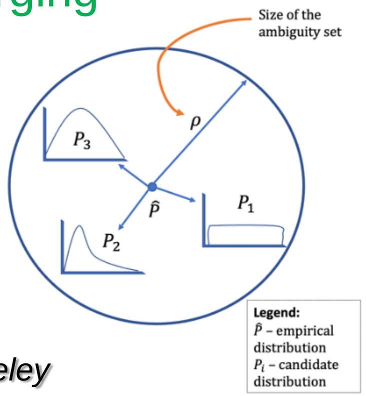
$$\min \quad \sum_{k\in\mathcal{K}}\sum_{i,j\in N, i\neq j} d_{ij}c_{ij}^{k}\, x_{ij}^{k}\, f_{e,dep} + \sum_{k\in\mathcal{K}}\sum_{i\in N} p^{rated} tb_i^k \left(f_{e,cus} - f_{e,dep}\right) + \sum_{k\in\mathcal{K}}\left(\tau_{arr}^{k} - \tau_{dep}^{k}\right) f_{driver}$$

Energy consumption cost | enroute charging | driver costs

One of the Constraints for BEV

$$\inf_{p\in\mathcal{P}} \mathbb{P}\left[b_j^k \leq b_i^k - \sum_{s\in\mathcal{S}} c_{ij}^{ks} x_{ij}^{ks} + p^{rated} tb_i^k + \left(1 - x_{ij}^{ks}\right) M \right] \geq 1 - \beta$$

Battery level from node i to node j



More data, more accurate energy distributions, less conservative routing/ dispatch, greater energy & GHG savings

Preliminary Results: Fleet Optimizer *Planning*

- Different scenarios e.g. fuel cost/carbon intensity, vehicle technologies and charging infrastructure will be considered in upcoming 2022 deliverables.
- Planning optimizer results are on one of the Venture fleet divisions (Division 27).
- Planning optimizer is done with a representative day of operation (Stochastic and learning is applied in Q3 2022 with POLARIS models integration)
- Scenario assumptions to highlight:
  - Fuel and electricity carbon intensities are current US National average.
  - Charging available only at depot.
  - CAV offers ~10% improvement in energy efficiency and reduces driver wage expenses by 80% at an initial cost of $50,000.
  - With CAV, driver hours of operation constraint is relaxed.

	Parameter	Units			
Constrains	Case Study	-	Baseline	Case 1	Case 2
	Powertrain Option	-	All Diesel ICE	Various PTs	Various PTs
	CAV	-	No	No	Yes
Outputs	No of Vehicles	-	9	9	7
	Vehicle Types	-	9 Diesel	7 Diesel + 2 BEV	1 Diesel + 5 Diesel CAV + 1 BEV CAV
			% Change w.r.t. Baseline		
	Fuel Consumed	gal/day	-	-22%	-23%
	Total Miles	miles/day		0%	0%
	Total Freight	US-ton		0%	0%
	WTW CO2	Ton CO2/day		-5%	-11%
	WTW CO2 Efficiency	kgCO2/(US-ton-100 mile)	-	-5%	-11%
	OPEX	$/Year	-	-2%	-46%
	CAPEX	$/Year	-	42%	28%
	Yearly Ammortized Cost	$/Year	-	7%	-29%

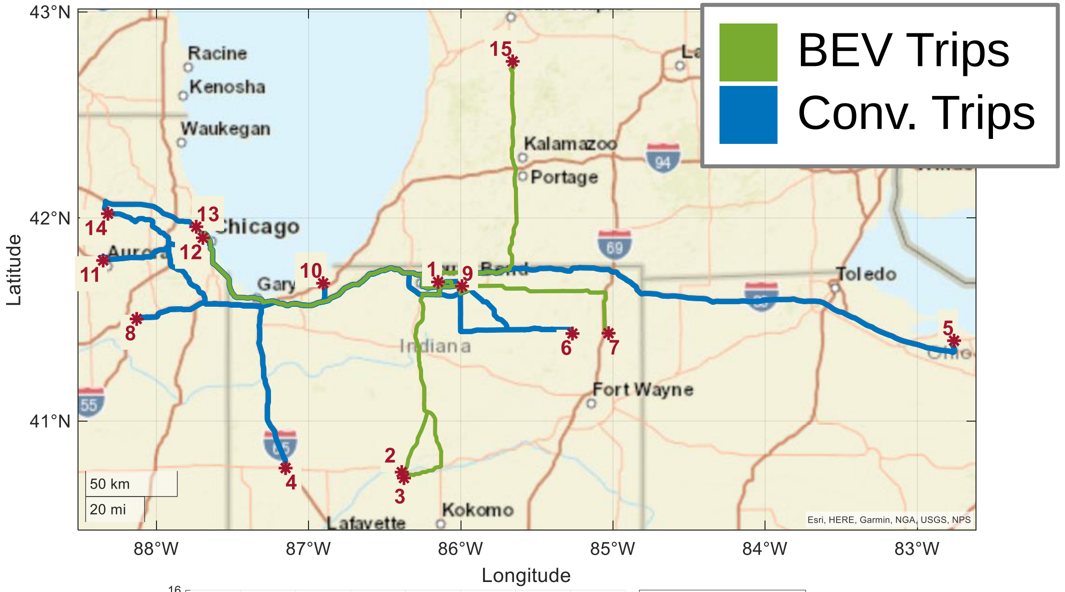
PT: Powertrain
CAV: Connected and Automated Vehicle
ICE: Internal Combustion Engine
BEV: Battery Electric Vehicle

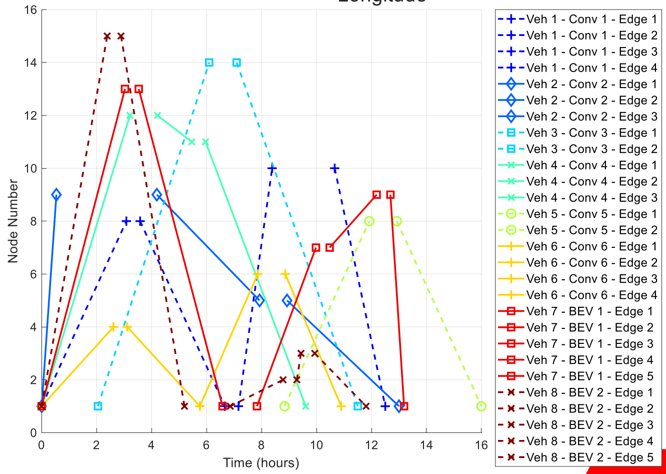
Preliminary Results: Fleet Optimizer *Daily*

Sample Day Comparison (Venture Division 27 Operation on March 5th 2021)

Baseline: *9 Diesel ICE Class 8 regional haul trucks.*
Optimized fleet (Case 1): *7 Diesel ICE + 2 Electric (BEV) regional haul class 8 trucks with charger at depot.*

Metrics	Fleet Level Comparison			Optimized Fleet Analysis			
	Baseline Fleet	Optimized Fleet		ICE		BEV	
	Total	Total	Change (%)	Contrib.	Contrib. (%)	Contrib.	Contrib. (%)
Cargo (U.S. ton)	201	201	0%	127	63%	74	37%
Shipment (Ton-mile)	18,670	18,670	0%	13,262	71%	5,407	29%
VMT (miles)	2,960	2,724	-8%	1,966	72%	758	28%
Electricity consumption (kWh)	-	1,433	-	-	-	1,433	100%
Fuel consumption (gal Diesel)	333	223	-33%	223	100%	-	-
WTW CO_2 (kg)	4,429	3,784	-15%	2,971	79%	813	21%
WTW CO_2 (kg / U.S. ton-100 mile)	**23.7**	**20.3**	**-15%**	22.4	-	15.0	-
OPEX ($)	$ 3,591	$ 3,192	-11%	$ 2,393	75%	$ 799	25%
Operating cost per mile ($/mile)	$ 1.21	$ 1.17	-3%	$ 1.22	-	$ 1.05	-





- 15% reduction in WTW CO_2 on this sample day with optimizing routing, BEV & ICE truck dispatching and cargo schedule.
- 8 out of 9 trucks are deployed with the optimized fleet at this day.
- The utilization of BEVs is maximized. Both BEVs are dispatched.
- Performance metrics will be represented by a distribution generated from different days of operation.

Collaboration with Other Institutions

- **Venture Logistics**, Support with insights on fleet logistics and operation, constraints and requirements for optimization and data collection to characterize the fleet operation and testing of the algorithms.

- **Argonne National Laboratory**, Support with the POLARIS-SVTrip-Autonomie fleet simulation models under different scenarios. Furthermore, Argonne is supporting fleet optimizer integration with POLARIS.

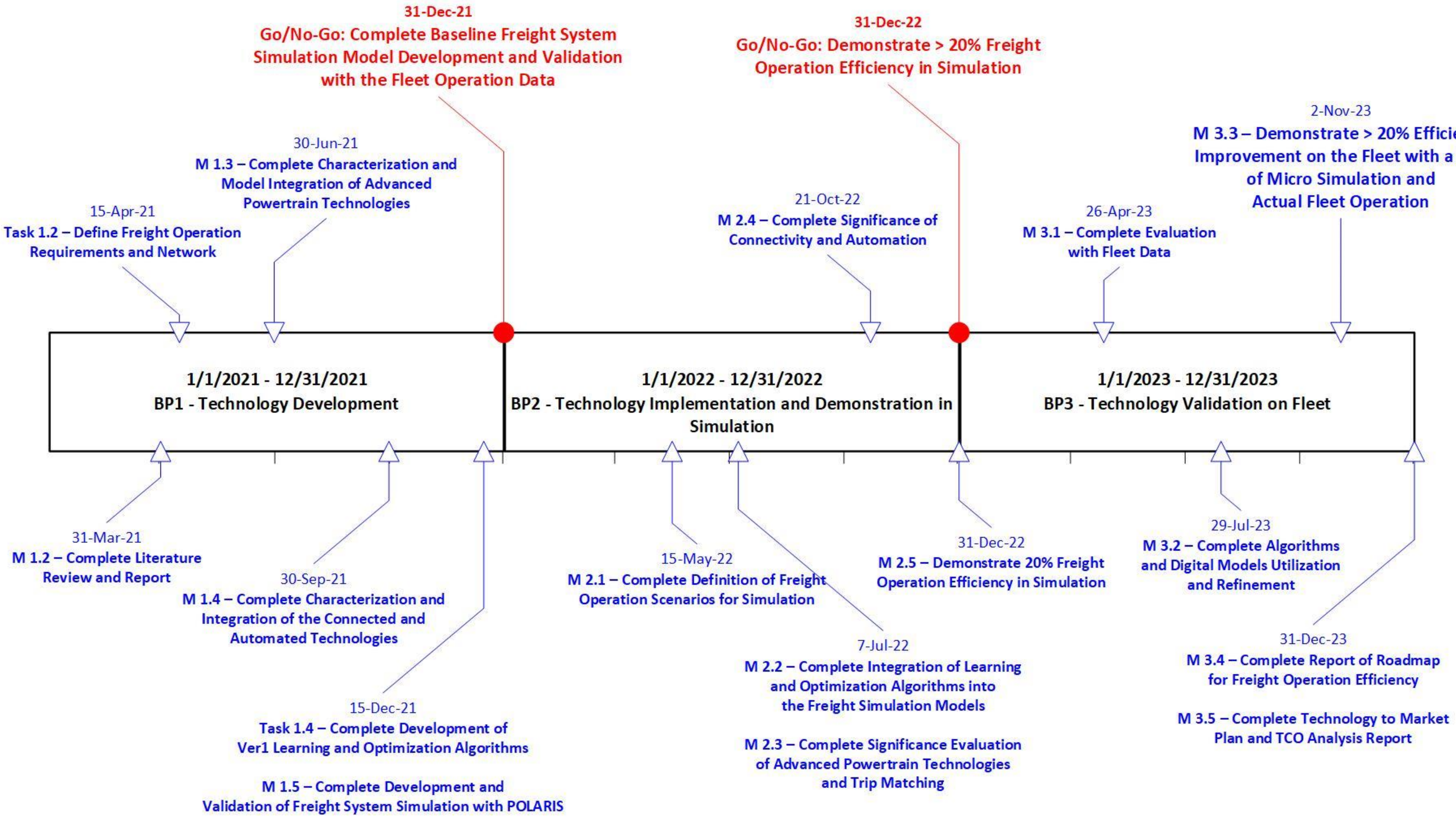
- **University of California Berkeley**, Support with the development and integration of innovative stochastic and learning algorithms for fleet optimizer.

- **Michelin North America,** Quantify the improvements in energy savings when accounting for information in real time about the tire locomotion capabilities and resistance to motion forces as a function of the vehicle operating conditions.

Remaining Challenges and Barriers

- Complete development and integration of learning fleet optimizer in POLARIS.
- Implement fleet optimizer on Venture operation to compare with the baseline.
- Innovate learning and optimization methods to address uncertainties and complexities in the fleet operation.
- Scaling learning and optimization methods to address the fleet large network operation.

Proposed Future Research*



*Any proposed future work is subject to change based on funding levels.

Summary

- Development and validation of the baseline fleet simulation models completed with POLARIS and fleet data.
- Connectivity and Automation (CAV) characterization completed for heavy duty truck applications. The models are used in the fleet optimizer and simulation (part of the path to target).
- Tire testing is ongoing at Michelin facilities to develop tire models with connectivity to integrate in the simulation.
- Scenario planning is ongoing to run the fleet optimizer under different business, fuel and technology future trends.
- Fleet optimizer integration with POLARIS is ongoing to demonstrate the project target in simulation by the end of 2022.

Thank You!

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